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HIGH FREQUENCY TUNNEL DEVICE STUDY

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## ABSTRACT

The work reported here is aimed at achieving low noise microwave amplification - specifically: 20 db gain, 6 db noise figure at 10 kMc, and 1 kMc bandwidth - by using tunneling. The program has two phases running concurrently. The first is aimed at an all solid state device, the second, at using a thin film cathode in conjunction with a microwave structure.

In accordance with the original work statement, the feasibility of the two approaches has been determined. Exploratory work has shown that the approaches taken in the first phase will not produce the required amplification without a long and expensive effort; accordingly, further work on this phase will be suspended. The results obtained in the second phase appear to be much more promising, and henceforward all of our efforts will be diverted to this approach.

### Phase I

The program on the solid-state amplifier during this period involved (1) an examination of the metal-base transistor, (2) growth of  $\text{Al}_2\text{O}_3$  films by plasma oxidation, (3) fabrication and testing of MIA structures with an evaporated CdS emitter, (4) fabrication and testing of MIA structures with an evaporated CdS collector, and (5) an exploratory effort to fabricate a thin-film analogue structure.

Metal-base transistor structures have been fabricated with Ge collectors, thin-film Au bases and single crystal Ge, Si, and evaporated CdS emitters. Active device behavior has been observed and reported.

Plasma oxidation of Al films deposited upon Ge has been performed. The resulting oxides are different from those grown thermally or with UV stimulation. Good tunneling characteristics have not been observed.

Metal-interface amplifier structures with evaporated CdS emitters have shown no improvement and still suggest that hot electrons are not involved in the current transfer mechanism.

### Phase II

Approximately 150 test cathode structures have been produced using the methods described in previous Technical Notes. Pulsed emission current densities of up to several amperes per square centimeter have been obtained. Lifetime remains a serious problem. It is

believed, however, that with improved uniformity of the tunneling insulator satisfactory operation of the tunnel cathode over extended periods should be possible.

The requirements on cathode dimensions and performance necessary to achieve 20 db gain at 10 kMc have been theoretically established. Work was performed towards fabricating emitting structures suitable for use as the cathode in such a tube.

Since the tunneling insulator appears to be one of the very critical elements in the production of a suitable tunnel cathode, a study of these layers was undertaken. Work was begun using an ellipsometer for determining the thickness of such films. Steps were taken towards forming electrically stronger insulator layers. This work was aimed primarily towards the study of different methods of oxidation of aluminum; as well as forming insulator layers different from  $\text{Al}_2\text{O}_3$ .

Experimental evidence about the distribution of emission over the emitting surface and the velocity distribution of the emitted electrons is required for evaluating the proper functioning of the cathode. To obtain this, work was begun towards building a projection tube and a set-up for measuring the velocity distribution by the retarding potential method.

From the results of experimental measures, attempts have been made to determine whether the  $\text{Al-Al}_2\text{O}_3\text{-Au}$  structure previously described is an advantageous one, and which basic factors are responsible for limiting the performance. A theoretical model is postulated to explain the functioning of this structure. A serious limitation of performance is imposed by the strong attenuation of the energetic electrons in the top metal film. A gold film of only fifty Angstroms thickness is expected to limit the transfer ratio to about ten percent. Basically, however, the  $\text{Al-Al}_2\text{O}_3\text{-Au}$  structure seems to give the right kind of operation.

## Table of Contents

<u>Section</u>		<u>Page</u>
	Part I. Solid State Amplifier (J. Lavine)	
I.	Introduction	1
II.	Metal-Base Transistor Studies	1
III.	$\text{Al}_2\text{O}_3$ Growth	5
IV.	Metal-Interface Amplifiers with CdS Emitters	7
V.	Metal-Interface Amplifier Structures Employing Evaporated CdS Collectors	10
VI.	Exploratory Device Configurations	10
VII.	Program Schedule	10
VIII.	Program for the Next Interval	14
	Part II. Amplification Using Thin Film Cathodes (W. Feist)	
I.	Long Term Objectives	15
II.	Work Performed During the Period Covered by the Report	15
	1. Outline of Objective and Approaches	15
	2. Results of Work Performed During the Report Period	16
III.	Conclusions and Work Planned for Next Quarter	34
	References	36

# List of Illustrations

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1.	Grounded-base characteristics of metal-base transistor #263. 100 Å of Au on one ohm-cm n-type Ge, 0.025 ohm-cm n-type Ge emitter.	3
2.	Grounded-base characteristics of metal-base 100 Å of Au on one ohm-cm n-type Ge, 1.7 ohm-cm n-type Si emitter.	4
3.	Characteristics of metal-base transistor #276. 100 Å of Au on one ohm-cm n-type Ge, 3000 Å of CdS emitter.	6
4.	Block diagram of plasma oxidation apparatus.	8
5.	Characteristics of MIA unit #274. 100 Å of Al on one ohm-cm n-type Ge, air grown oxide, 3000 Å of CdS over Al <sub>2</sub> O <sub>3</sub> , after forming action	9
6.	MIA Structure with evaporated CdS collector.	
7.	Grounded-base characteristics of MIA with evaporated CdS collector.	12
8.	Thin-film analogue or Spacistor structure.	13
9.	Breakdown voltage vs. oxidation time in dry and wet oxygen atmosphere for oxide film grown on aluminum film. Temperature ~ 26°C. The test was operated after the sample had stayed in air for 1 day after fabrication.	19
10.	Breakdown voltage vs. time of exposure of aluminum films to a gas discharge in oxygen atmosphere (~150 mA, 2 kv). The deviation in the oxidation rates may be due to changes in the strength of the ion bombardment with the position of the sample.	20
11.	Abnormal V-I characteristic of an Annular tunnel emitter featuring a negative resistive region.	23
12.	Typical initial diode and emission characteristics of annular tunnel emitter. Display time: 500 μsec. Au-film thickness: 90 Å.	24

List of Illustrations (cont.)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
13.	Deterioration of Emission from an Annular tunnel cathode under pulsed operation. Width of the rectangular pulses: 0.1 millisec, duty cycle: 1.2%, diode voltage: 7.5 volts, diode current: 70 mA.	26
14	Deterioration of emission from an annular tunnel cathode under pulsed operation. Width of the rectangular pulses: 1 millisec, duty cycle: 11%, diode voltage: 7.3 volts, diode current: 70 mA.	27
15.	Basic energy diagram of a tunnel cathode	30

# HIGH FREQUENCY TUNNEL DEVICE STUDY

## Part I. SOLID-STATE AMPLIFIER (J. Lavine)

### I. Introduction

The program on the solid-state amplifier during this report period involved (1) an examination of the metal-base transistor (thermonic or Schottky injection of hot electrons), (2) growth of  $\text{Al}_2\text{O}_3$  films by several techniques and a comparison of their electrical properties, (3) fabrication and testing of metal-interface amplifier structures using a CdS thin-film emitter, (4) the fabrication and testing of metal-interface amplifier structures involving evaporated CdS collectors, (5) an initial exploratory effort to fabricate an analogue or Spacistor structure employing thin-film techniques. These will be described in order.

### II Metal-Base Transistor Studies

Recently Moll<sup>1</sup> and Atalla<sup>2</sup> analyzed the high frequency potential of the metal-base transistor and theoretically concluded that it may exceed both the bipolar junction transistor and tunnel-emission devices in high-frequency performance. As described in Technical Note #2, the metal-base transistor makes use of hot-electrons generated by a Schottky or metal-semiconductor barrier. Basically, the promise of high frequency performance comes about in the following manner. Both the metal-base transistor and tunnel-emission devices such as the metal-interface amplifier employing metal thin-film base regions have much lower base resistance than junction transistors. In the case of tunnel-emission devices, the tunneling requirement demands metal-oxide-metal layers with input capacities in the range of  $1\mu\text{f}/\text{cm}^2$ . Even though the total capacity may be minimized by size reduction of the emitter, the input charging time will be larger than for the non-tunneling Schottky emitter. In this case, the input capacity corresponds to that of the semiconductor space-charge region with a thickness of the order of a few thousand Angstroms compared with a few tens of Angstroms for the tunneling emitter. As a consequence, for roughly equal emitter to collector transit times and collector charging time, the calculated high frequency performance of the metal-base transistor exceeds that of the metal-interface amplifier. Using similar arguments, the metal-base transistor high frequency capability may also exceed that of the junction

(1) J. Moll, "Comparison of Hot-Electron and Related Amplifiers"  
IRE-PGED Electron Devices Meeting, Washington, October 1962.

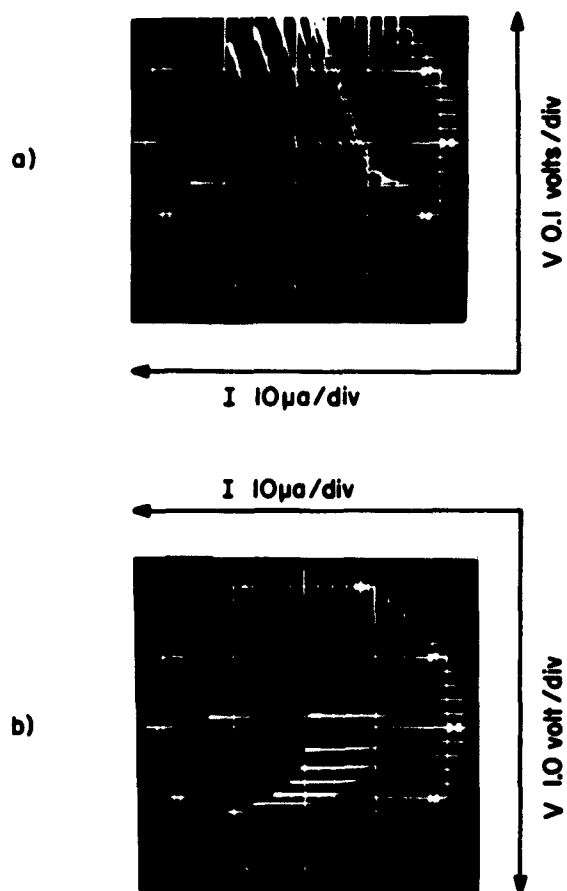
(2) M. M. Atalla, NEREM Record 4, 162 (1962)

transistor. Arguing along the same line, the depletion-layer transistor version of the metal-interface amplifier will also permit a small emitter charging time. However, if the injected current is space-charge limited, transit-time effects may be different in the collector space-charge region.

During this period, metal-base structures were fabricated upon 1 ohm-cm n-type Ge substrates with chemically polished surfaces. Gold was used predominantly as the base film because of its long hot-electron mean-free-path<sup>3, 4</sup> (740 Å). Units with base films of Au ranging from 100 to 400 Å were measured. Several runs were also made with Ag base films with mean-free-path<sup>4</sup> for hot electrons roughly one-half that of Au. Several different emitter semiconductors were employed. N-type Ge, n-type Si and n-type CdS single crystals, electrochemically sharpened, were micromanipulated into position to serve as emitter contacts in a manner similar to that reported by Atalla<sup>5</sup> and Geppert.<sup>6</sup> Care was taken in all cases to keep the input current below 500 µa/step in order to minimize forming action at the emitter. Figure 1 shows the grounded-base collector and transfer characteristics of unit #263 consisting of 100 Å of Au on 1 ohm-cm n-type Ge with a 0.025 ohm-cm n-type Ge point emitter. Units with 100 Å Au base films exhibited grounded-base current transfer ratios of the order of a few tenths. In several cases, grounded-emitter collector characteristics exhibited the so-called crossover, indicative of active device behavior. In all cases, current transfer was so small as to negate all possibility of power gain. In many cases, the output characteristics changed during measurements, with visible indication of film damage below the emitter point contact. In all cases, the emitter-base contacts exhibited good diode characteristics. Current transfer on thicker Au base films (200 - 400 Å) was always negligibly small. Again, in those cases where current transfer was obtained, it was always possible to detect some evidence of the previous presence of the semiconductor emitter. Figure 2 shows the grounded-base collector characteristics of unit #261 consisting of 100 Å of Au on 1 ohm-cm n-type Ge with a 1.7 ohm-cm n-type Si emitter. In this case,  $\alpha$  of about 0.5 was obtained with  $v_{eb} - i_c$  characteristics showing strong positive feed-back effects.

- (3) W. G. Spitzer, C. R. Crowell and M. M. Atalla, Phys. Rev. Ltrs. 8, 62 (1962)
- (4) C. R. Crowell, W. G. Spitzer, L. E. Howarth and E. E. LaBate, Phys. Rev. 127, 2006 (1962)
- (5) M. M. Attala and D. Kahng "A New Hot Electron Triode with Semiconductor-Metal Emitter" IRE-AIEE Solid-State Device Research Conference, Durham, N. H. July 1962.
- (6) D. V. Geppert, Proc. IRE 50, 1527 (1962)

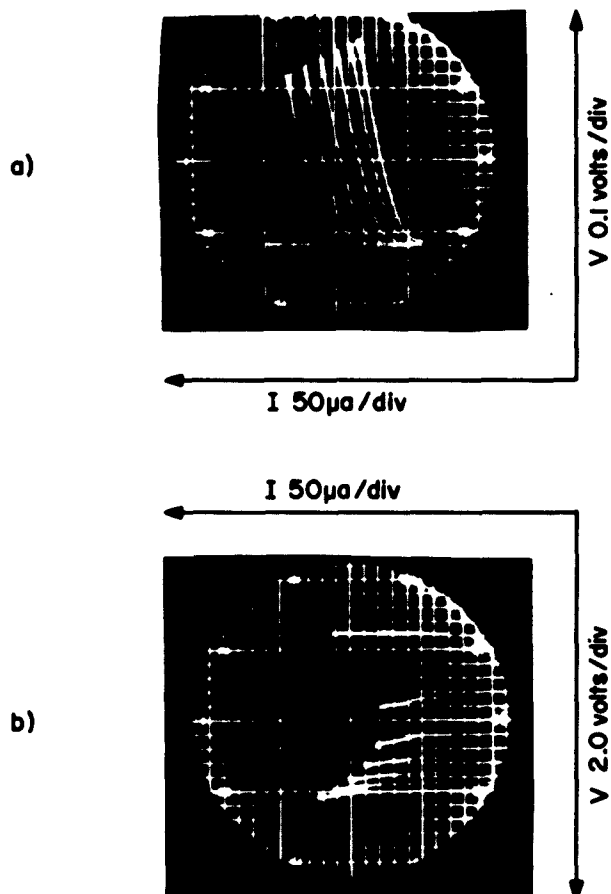




a) Collector characteristics , input  $200\text{ }\mu\text{a}$  / step  
 b) Transfer characteristics , input  $200\text{ }\mu\text{a}$  / step

GROUNDING-BASE CHARACTERISTICS OF METAL-BASE TRANSISTOR  
 #263. 100 Å OF Au ON 1 OHM-CM N-TYPE Ge, 0.025 OHM-CM  
 N-TYPE Ge EMITTER.

FIGURE 1



- a) Collector characteristics, input  $100\mu\text{A}/\text{step}$   
 b) Transfer characteristics, input  $100\mu\text{A}/\text{step}$

GROUNDING - BASE CHARACTERISTICS OF METAL - BASE TRANSISTOR  
 #261. 100 Å OF Au ON 1 OHM-CM N-TYPE Ge, 1.7 OHM-CM  
 N-TYPE SI EMITTER.

FIGURE 2

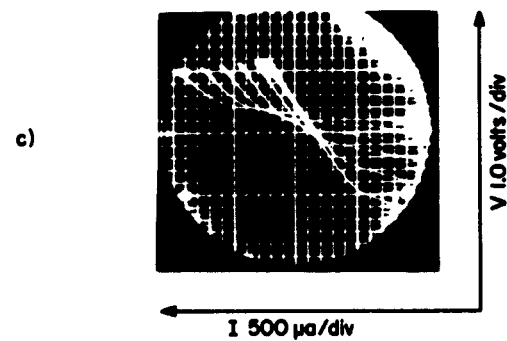
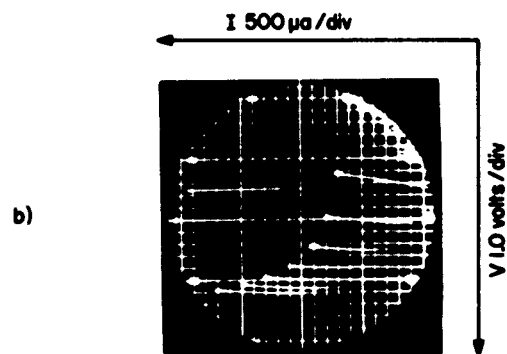
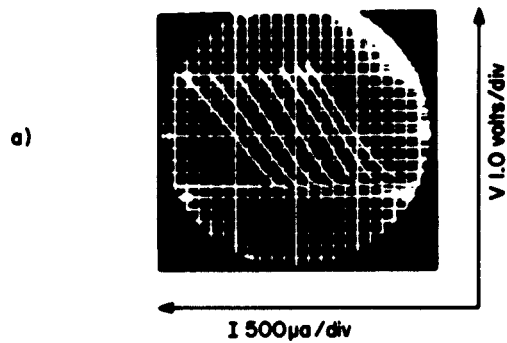
The shortcomings of micromanipulated semiconductor emitter points led to the use of evaporated CdS emitters. CdS ranging from 3,000 to 10,000 Å in thickness was evaporated onto the metal base films through suitable masks. Because of the difficulties reported in Technical Note #2, contact to the CdS was made with a tungsten point contact or with a small In sphere. In virtually all cases, the Au-CdS-tungsten point showed poor diode characteristics with very small rectification ratio, while the In-CdS-Au showed rectification sometimes and space-charge-limited characteristics at other times. Typically, no current transfer was obtained until the unit was driven at high currents, of the order of 50 - 100 ma, at which time alterations of the output characteristics would occur and both grounded-base and grounded-emitter current transfer was observed. Figure 3 shows the characteristics of unit #276 consisting of 100 Å of Au on 1 ohm-cm n-type Ge with 3000 Å of CDS on the Au after the so-called forming action. The grounded-emitter collector characteristics provide evidence of active device behavior, even though the current transfer ratio ( $\sim 0.15$ ) is insufficient to obtain power gain. At present, the behavior is not at all understood. If the emitter point is relocated on the same CdS mesa, the forming action must be repeated. In view of the thickness range, 3,000 - 10,000 Å, on which this behavior was observed, we cannot presume that the W point on the CdS shorted through the CdS. Speculatively, it appears that different conducting behavior is built into the CdS in the immediate vicinity of the point.

Two runs were made with a 100 Å Ag base film and 3,000 Å of CdS on top of the Ag. Generally, the collector surface-barrier diodes were poor, and no cross-over effects were observed in grounded-emitter operation. Small current transfer was observed in grounded-base measurements, but this alone does not signify active device behavior.

### III. Al<sub>2</sub>O<sub>3</sub> Growth

As indicated in the previous Technical Notes, the lack of a method for growing an oxide which permits control over a range of thickness from tunneling to non-tunneling has been a serious handicap to the fabrication of many device configurations. Desirably, the technique should permit the growth of an oxide on any of several metals, including Au. This suggests the use of an evaporative technique using materials such as SiO. We have attempted to make tunneling structures using evaporated SiO and encountered the typical problems of non-uniformity, shorted areas, etc. During this period, we set up to perform O<sub>2</sub> plasma oxidation of Al as reported by Miles et al<sup>7</sup>. The Kinney evaporator was equipped with suitable control values to emit Matheson research grade O<sub>2</sub> after pumping down. The dc discharge configuration consisted of an Al ring and the base-plate of the evaporator. The Ge samples with evaporated Al, mounted

(7) Miles, Shapiro, Smith and Nicol, "High Frequency Superconducting Negative Resistance Devices" IRE-AIEE Solid State Device Research Conference, Durham, New Hampshire, July 1962.



- a) Grounded-base collector characteristics, input 5ma/step  
 b) Grounded-base transfer characteristics, input 5ma/step  
 c) Grounded-emitter collector characteristics, input 5ma/step

CHARACTERISTICS OF METAL-BASE TRANSISTOR #276. 100Å OF Au ON  
 1 OHM-CM N-TYPE Ge, 3000Å CdS EMITTER.

FIGURE 3

on metallic headers were insulated from the base-plate and maintained at a potential a few volts above ground. After flushing the bell jar with O<sub>2</sub> several times, the bell jar was evacuated to about 10<sup>-5</sup> torr and O<sub>2</sub> was emitted to a pressure of about 200 microns. About two kilovolts dc (approximately 10 ma) was sufficient to initiate the discharge between the Al ring and the base plate. According to Miles et al, the oxide growth occurs at the rate of 23 Å/volt of potential difference between the samples and the base plate. Figure 4 shows a block diagram of the system used.

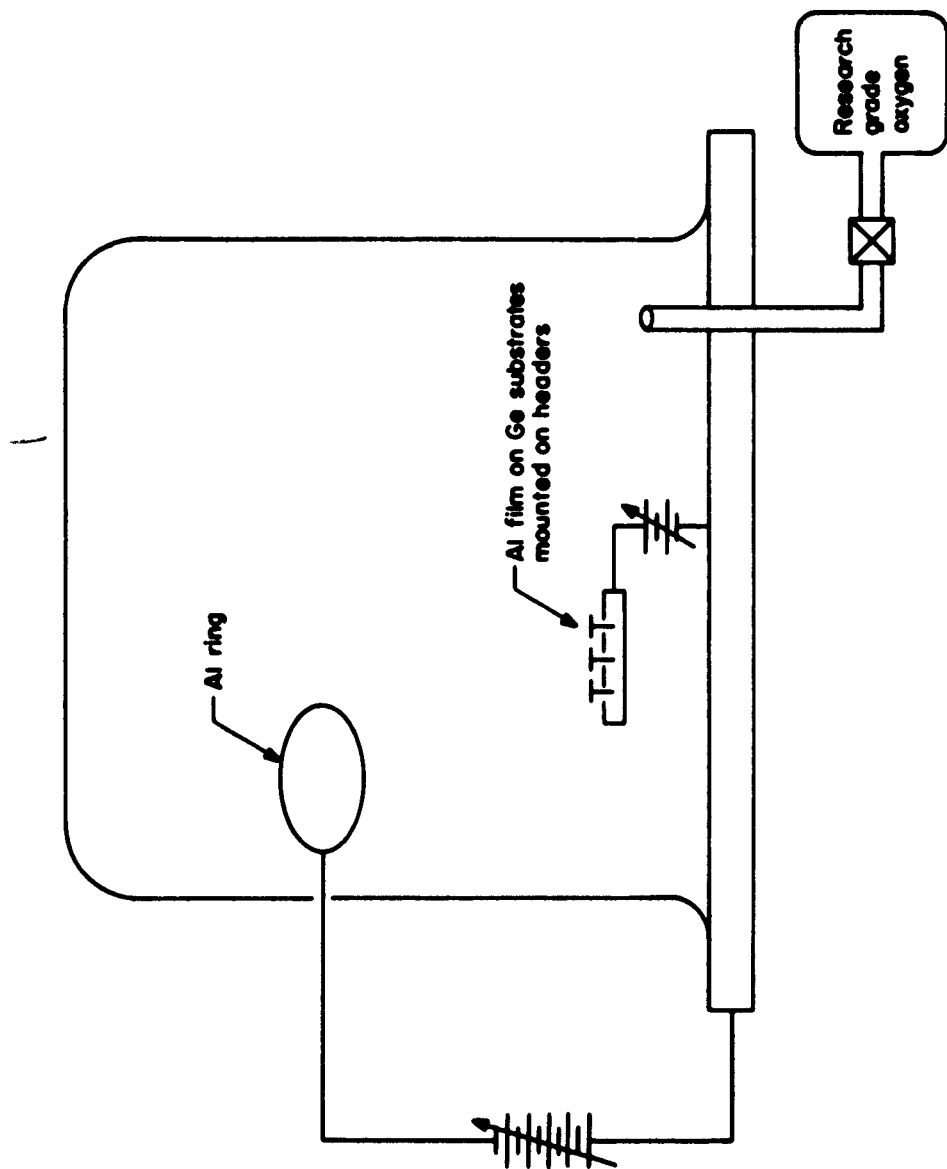
Because of previous difficulty with oxidation of Al films greater than 200 Å thick, 300 Å of Al was chosen as the substrate film thickness. Control runs were made on samples oxidized in air at 300°C for 12 hours and exposed to UV at room temperature for 1.5 hours. Plasma oxidation was performed at 1.5, 3.0 and 4.5 volts. During these tests of the oxide thickness, three types of contacts were placed on the Al<sub>2</sub>O<sub>3</sub>. Au paste contacts, evaporated Pb contacts as reported by Handy<sup>8</sup> and small In spheres at the end of a tungsten wire positioned with a micromanipulator, were used.

In a typical run, the breakdown voltage of several mesas on each oxide was measured. With Pb contacts, both the 1.5 and 3.0 volt plasma oxides exhibited breakdown at 9 volts, while the 4.5 volt oxide exhibited breakdown at about 10 volts. With an In sphere contact, the breakdown voltage tended to increase slightly with increasing oxidation voltage, but more in the ratio of 7:9:11 than 1.5:3:4.5 as would be roughly expected. No correlations were established with the Au paste contacts or with the control samples. At present, we may state only that work is continuing on the growth of Al<sub>2</sub>O<sub>3</sub> films but very little understanding of the cause of the difficulties has been elicited from our various experiments.

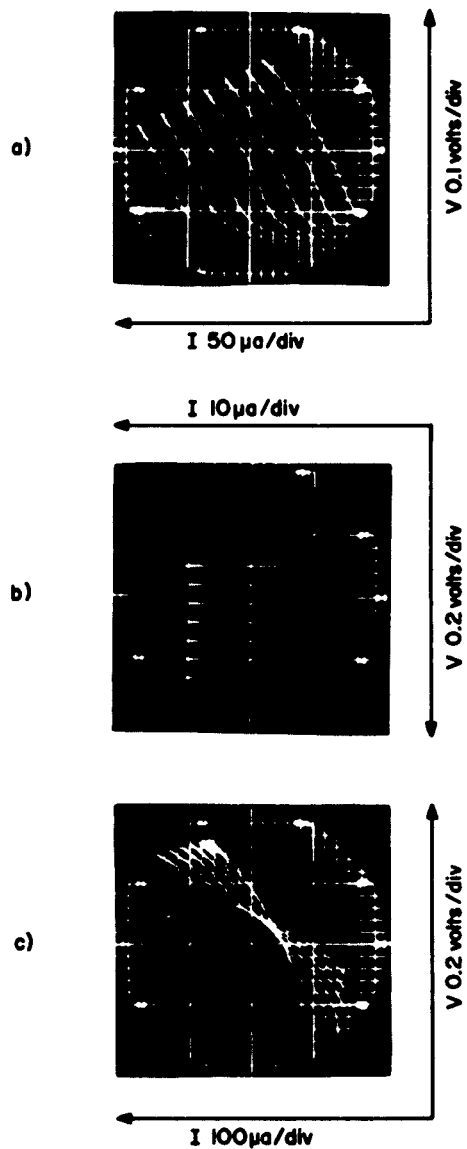
#### IV. Metal-Interface Amplifiers with CdS Emitters

Additional units to those reported in Technical Note #2 were fabricated with CdS evaporated emitters. Virtually all of the units exhibited current transfer of the order of 0.5 after forming. Grounded-emitter collector characteristics showing crossover effects were obtained in most cases. Figure 5 shows a series of characteristics taken on unit #274 consisting of one ohm-cm n-type Ge, 100 Å of Al with an air grown oxide and 3000 Å of CdS. In virtually all cases, reverse  $\alpha$  and  $\beta$  were also obtained, signifying that hot-electron behavior was not responsible for current transfer.

(8) R. M. Handy, Phys. Rev. 126, 1968 (1962)



BLOCK DIAGRAM OF PLASMA OXIDATION APPARATUS  
FIGURE 4



- a) Grounded-base collector characteristics, input  $200 \mu\text{A}/\text{step}$
- b) Grounded-base transfer characteristics, input  $200 \mu\text{A}/\text{step}$
- c) Grounded-emitter collector characteristics, input  $100 \mu\text{A}/\text{step}$

CHARACTERISTICS OF MIA UNIT #274, 100 A OF Al ON 1 OHM-CM N-TYPE Ge, AIR GROWN OXIDE, 3000 A OF CdS OVER  $\text{Al}_2\text{O}_3$ , AFTER FORMING ACTION.

FIGURE 5

## V Metal-Interface Amplifier Structures Employing Evaporated CdS Collectors

Several fabrication runs were made to achieve the device configuration shown in Figure 6. Onto glass microscope slides about 800 Å of In was evaporated. Then an evaporation mask with circles of about 100 mils was positioned on the In, and 800 Å of CdS was evaporated through the mask. A second mask was positioned and 100 Å of Al was evaporated. Finally, Au paste emitters were positioned partly on the Al and Al<sub>2</sub>O<sub>3</sub> and partly on the CdS. A subsequent heat treatment alloyed the In into the CdS slightly and removed the binder from the Au. The Al-Al<sub>2</sub>O<sub>3</sub>-Au I-V characteristics were not unlike those on Ge substrates. In most cases, however, the Al-CdS-In I-V characteristics were not suitable for collector use. This led to a brief study of the I-V characteristics of CdS films. Figure 7 shows the grounded-base collector and transfer characteristics of one unit. No grounded emitter characteristics were obtained on these units.

## VI Exploratory Device Configurations

During this period, we also fabricated a few device configurations embodying analogue or Spacistor principles. Figure 8 shows a cross-section of this device. The structure consists essentially of an emitter, a collector and a grid. One method of establishing the grid structure consists of making use of pin-holes known to occur in thin metallic films. Another way is to deposit a suitable grid-like structure by masking the evaporation, i. e., two evaporations with the mask rotated by 90°. A third method is to establish the grid using photolithographic techniques. Depending upon the electrical characteristics of the grid and the CdS either of two modes of operation might occur. If the grid established a suitable space-charge region only in the near vicinity of the grid, then analogue<sup>9</sup> action would occur (as in a field-effect transistor). If, on the other hand, the field applied between the grid and the cathode extended significantly close to the cathode, then modulation of the space-charge limited current could obtain. A similar device has recently been proposed by Wright.<sup>10</sup>

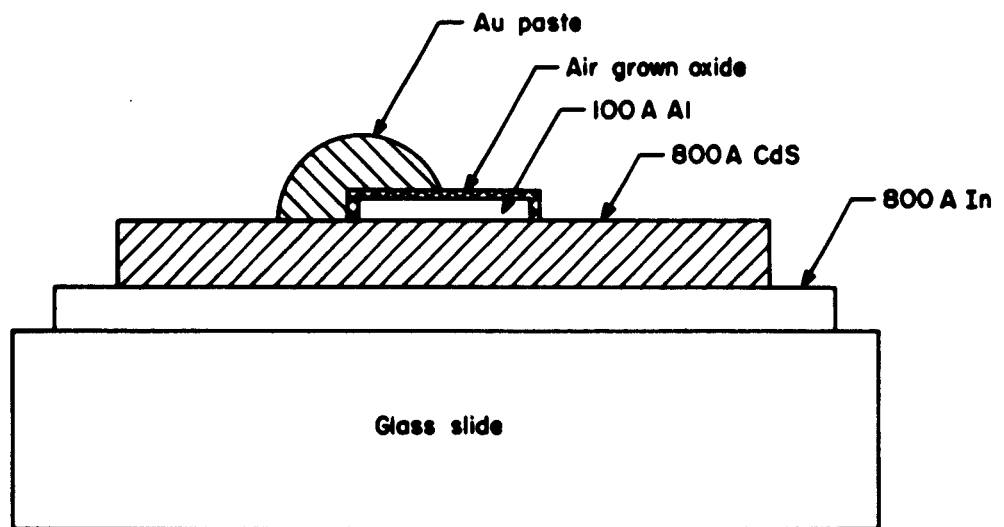
## VII Program Schedule

The evaluation of solid-state thin film amplifiers has been completed in accordance with the program schedule.

(9) W. Shockley, Proc. IRE 40, 1289 (1952).

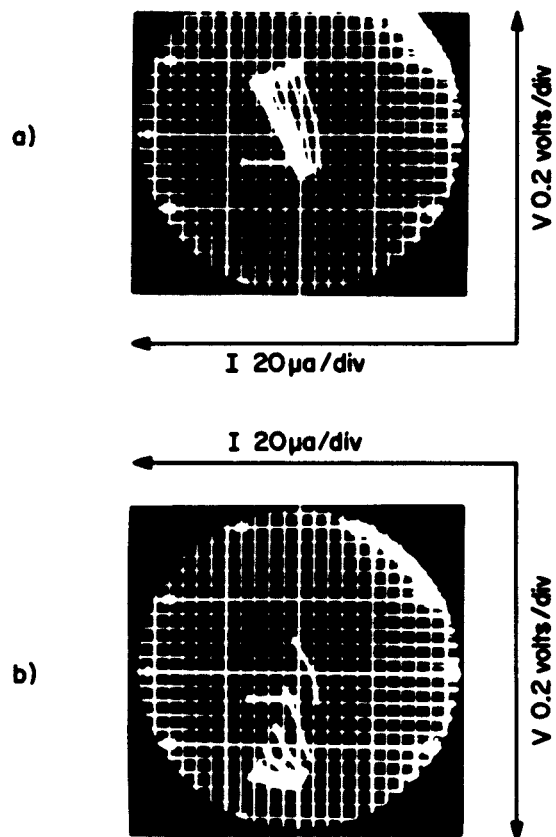
(10) G. T. Wright, Solid-State Elect. 6, 117 (1962).





MIA STRUCTURE WITH EVAPORATED CdS  
COLLECTOR

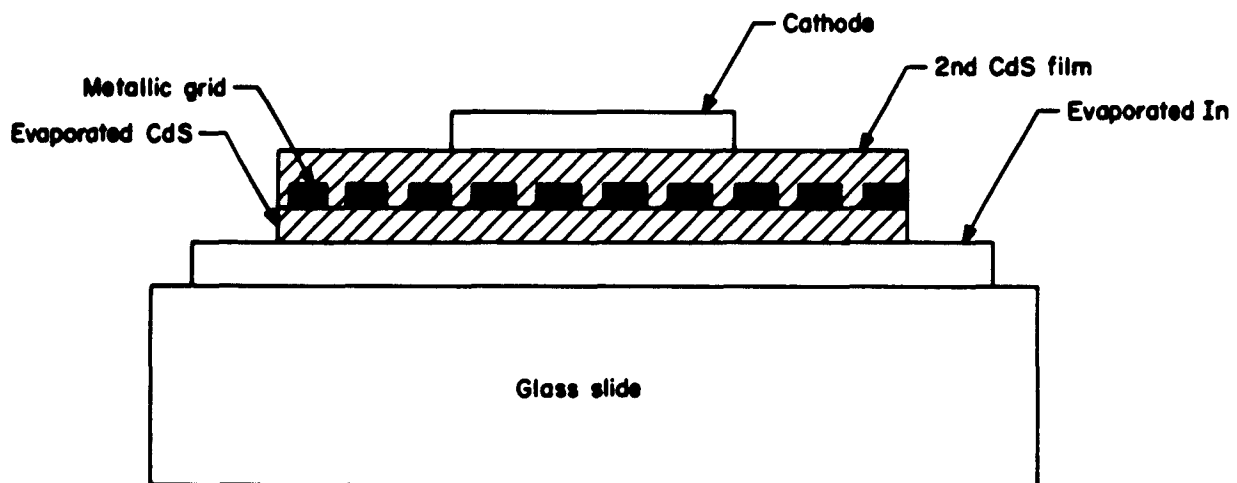
FIGURE 6



- a) Collector characteristics , input 20  $\mu$ a / step  
 b) Transfer characteristics , input 20  $\mu$ a / step

GROUNDING - BASE CHARACTERISTICS OF MIA WITH EVAPORATED  
 CdS COLLECTOR.

FIGURE 7



THIN-FILM ANALOGUE OR SPACISTOR STRUCTURE  
FIGURE 8

### VIII Program for the Next Interval

In accordance with the original work statement, the feasibility of the two approaches has been determined. Exploratory work has shown that the approaches taken in this phase will not produce the required amplification without a long and expensive effort. Accordingly, further work on this phase will be suspended. The results obtained in the second phase appear to be much more promising, and henceforward all of our efforts will be diverted to this approach. During the next interval, emphasis will be placed on the materials aspects of the program which are clearly limiting our ability to fabricate the several proposed and investigated device configurations.

Part II. AMPLIFICATION USING THIN FILM CATHODES  
(W. Feist)

I. Long Term Objectives

The work reported in this section is aimed at achieving low-noise microwave amplification - specifically: 20 db gain, 6 db noise figure at 10 kMc, and 1 kMc bandwidth - by using a thin film cathode in conjunction with a microwave structure. The thin film cathode shall be operated under dc-conditions to emit a steady electron beam of low initial noisiness. This will then be passed through a microwave structure to interact with an electromagnetic excitation on the latter, as in a conventional traveling-wave tube.

II. Work Performed During the Period Covered by the Report

1. Outline of Objective and Approaches

In the previous Technical Note, initial findings concerning the emission characteristics from Al-Al<sub>2</sub>O<sub>3</sub>-Au structures were reported. Work during this quarter was aimed at a possible theoretical model to explain the functioning of this structure. From the results, attempts were made to determine whether the structure previously described was an advantageous one, and which basic factors were responsible for limiting the performance. The necessary information was derived by experimentally evaluating the effect of various insulator and metal thicknesses, as well as the reducing of the work function into the vacuum of the top metal film.

For a detailed correlation of the experimentally-observed characteristics with the theory, an accurate knowledge of the structural parameters is necessary, one of the most important ones being the thickness of the tunneling insulator. To this end, a study of the use of the ellipsometer for the measurement of thin films has been initiated. Additionally, considerable efforts were directed towards improving fabrication methods.

Experimental evidence about the distribution of the emitted electrons is required for evaluating the proper functioning of the cathode. To obtain this, work was begun towards building a projection tube and a set-up for measuring the velocity distribution of the emitted electrons by the retarding potential method.

Life tests have been performed on the currently-available cathode structures. Since the cathode life was found to be unsatisfactory, steps were undertaken to form electrically stronger insulator layers for tunneling. This work was directed primarily towards the study of different methods of oxidation of aluminum; as well as towards methods of forming insulator layers different from  $\text{Al}_2\text{O}_3$ .

With respect to a practical cathode for a traveling-wave tube, the requirements on cathode dimensions and performance necessary to achieve 20 db gain at 10 kMc have been theoretically established. Work was performed towards fabricating emitting structures suitable for use as the cathode in such a traveling-wave tube.

## 2. Results of Work Performed During the Reporting Period

### (a) Fabrication of Tunnel Cathodes

#### (1) Fabrication of Cathodes for Testing.

Approximately 150 cathode structures of  $10^{-3}\text{cm}^2$  active area have been produced by employing the photomasking process as described in the previous reports. The base aluminum film is deposited onto optically polished pyrex substrates in a starting vacuum of  $10^{-8}$  Torr. During the fast evaporation ( $\approx 1000 \text{ \AA}/\text{sec}$ ) of the aluminum from a tungsten heater, the pressure rises to the  $10^{-5}$  Torr scale for short periods. The system is pumped by a 400 liter/sec VacIon pump. The tunneling insulator is produced by anodic oxidation in tartaric acid or by oxidation in air, depending on the oxide thickness required. The top gold film is produced by rapid evaporation in a vacuum better than the  $10^{-7}$  range.

#### (2) Fabrication of Cathodes for Use in a Microwave Tube

A small number of annular tunnel emitters of the dimensions shown in Figure 26 of the Technical Note #2 were fabricated on a substrate which can be fitted into a microwave tube. This required the exact positioning of the emitting area on a pyrex disc whose dimensions were chosen as follows: .396" diameter, .125" thickness. In order to attach a contact to the thin gold film on the top of the structure in such a way that it would not interfere with the focusing structure in the tube, a hole was provided in the center of the substrate through which the lead to the Au-film is fed. As will be discussed in part (c) of this section, the dimensions of this annular emitting area is too large for a useful tube working at 10 kMc with 20 db gain. However, it can be incorporated in a setup soon to be available to this laboratory for measuring the noise of such a cathode. No major difficulties appear to exist in reducing the size of the structure to the dimensions necessary for the 10 kMc tube, and efforts in this direction are under way.

### (3) Film Substrate Preparation

Aluminum films serving as base for tunnel cathodes have also been prepared in a newly obtained vacuum system. The system employs silicone oil diffusion pumps, and the pumping speed is of the order of 1500 liters/sec. A starting pressure for evaporation in the  $10^{-10}$  Torr range can be obtained. During the rapid evaporation of aluminum, the pressure rises to the  $10^{-8}$  Torr range as measured by a bare ion gauge mounted in the bell jar. In the system, cleaning of the substrates can be performed by an ion discharge and by heating to  $400^{\circ}\text{C}$  and higher.

The performance of the first batches of tunnel cathodes prepared using this system was not as satisfactory as the ones previously produced in the ionically pumped system. The transfer ratio was generally smaller, and the devices behaved less uniformly. Presumably, there was a difficulty with oil vapor in the system during the initial time of operation. This was also apparent from oil condensing in visible quantities on some parts in the bell jar, e. g. on the feedthroughs.

After repeated use of the system, this difficulty seemed to vanish; originally, it might have been caused by oil spilling into improper places during the transport. Recent tests on oil contamination in the system by evaporating a set of gold stripes on a substrate and evaporating a second set of gold stripes crossing the first ones produced no evidence of an insulating oil layer between the gold stripes. Also, a piece of polished stainless steel did not lose its wettability by water after being subjected to a vacuum cycle in the system. These tests were performed under adverse conditions; namely, no liquid nitrogen was used in the cold traps. Therefore, one can now be quite confident that oil contamination is no longer a problem. Films of satisfactory appearance have been recently produced in the system and are awaiting electrical testing.

Some work has been performed to evaluate the influence of the grain size of the base aluminum film with respect to the cathode performance. In one case, a film of an initially fine grain size was subjected to baking at  $400^{\circ}\text{C}$ . Grain growth by recrystallization was apparent after the treatment. The devices produced with this film showed about the same transfer ratio as the ones prepared on a fine grained aluminum film; however, they were much less stable. In a different experiment, the aluminum was evaporated onto a pyrex substrate held at  $200^{\circ}\text{C}$ . The film also was of rather large grain size and had a dull, bluish appearance. Devices produced on this film initially behaved quite normally; however, an abnormal decrease amounting to about 30% on the original transfer ratio was observed after a period of two days.

#### (4) Preparation of Tunneling Films

In using  $\text{Al}_2\text{O}_3$  as a tunneling insulator, a rapid deterioration of its electric properties is experienced when it is exposed to the high tunneling field strength of the order of  $10^7$  V/cm for periods approaching a few tenths of a second or longer. It has been suggested in the literature that water constituents in oxide films grown anodically in aqueous solutions may be responsible<sup>13</sup>. Therefore, efforts were made to produce the necessary oxide layer of 60 to 90 Å thickness by other methods.

One method consisted of exposing the aluminum films to a slow stream of dry oxygen at room temperature over an extended period. The breakdown voltage vs time of oxide growth of films prepared in this way is plotted in Figure 9. The curve follows the parabolic law of oxidation, and very long oxidation periods are required to obtain a tunneling voltage in excess of 4.5 Volts.

A second method of oxidation was evaluated which involves the exposure of the aluminum film to the ionic bombardment in a discharge in oxygen. Figure 10 represents some results giving breakdown voltage vs time of exposure to the discharge. The discharge used is driven from an ac power supply operating at 150 mA and 3 kV. The electrodes are shielded to protect the specimen from electron bombardment. As yet the quality of tunneling films obtained in this fashion has not been evaluated.

#### (5) Thickness Measurement of the Tunneling Insulator by the Ellipsometer Method.

The ellipsometric method to determine the thickness of thin films makes use of the fact that even a film of only Angstrom units in thickness deposited onto a substrate can markedly change the original polarization of light reflected from a substrate before the film was deposited. However, the application of the method is not straightforward and, generally, it is quite laborious to convert the instrument readings into thickness.

Although an extensive survey of the existing literature on ellipsometry has not yet been completed, preliminary studies have yielded the following convenient methods of calibration:

1. A. Vasicek<sup>15</sup> has published tables from which the index of refraction and thickness of a non-absorbing thin film on a particular glass can be determined from ellipsometer measurements of  $\Delta$  and  $\psi$ . Here,  $\Delta$  describes the phase shift between components of an ellipse, and  $\psi$  describes the position of the ellipse. Steps are being taken to obtain the proper glass for this measurement.



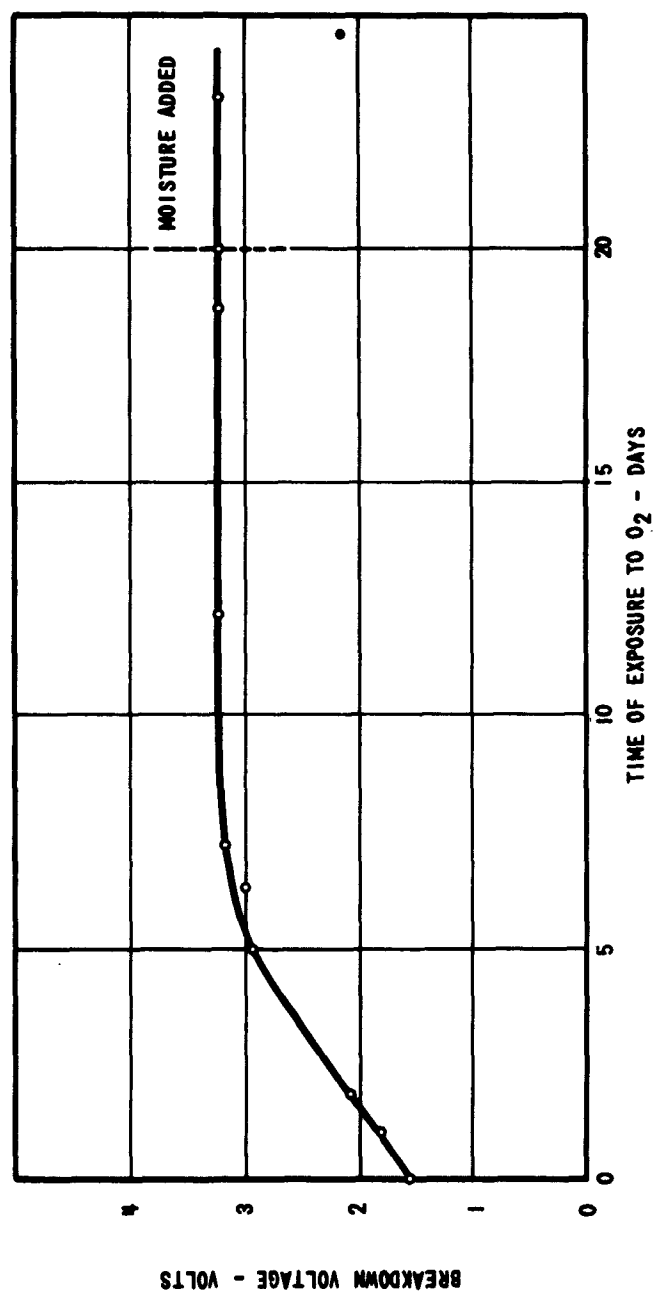


FIGURE 9 BREAKDOWN VOLTAGE vs. OXIDATION TIME IN DRY AND WET OXYGEN ATMOSPHERE FOR OXIDE FILM GROWN ON ALUMINUM FILM. TEMPERATURE  $\sim 26^{\circ}C$ . THE TEST WAS OPERATED AFTER THE SAMPLE HAD STAYED IN AIR FOR 1 DAY AFTER FABRICATION.

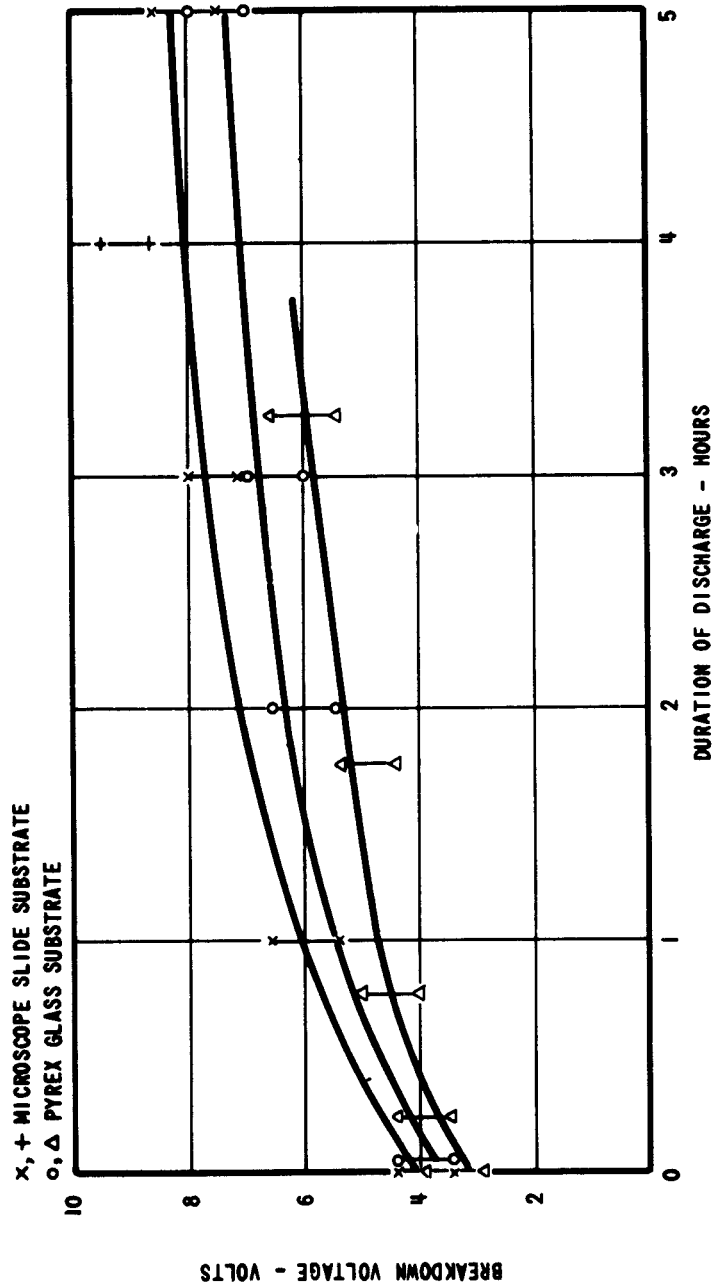


FIGURE 10 BREAKDOWN VOLTAGE vs. TIME OF EXPOSURE OF ALUMINUM FILMS TO A GAS DISCHARGE IN OXYGEN ATMOSPHERE ( $\sim 150\text{mA}, 2\text{kV}$ ). THE DEVIATION IN THE OXIDATION RATES MAY BE DUE TO CHANGES IN THE STRENGTH OF THE ION BOMBARDMENT WITH THE POSITION OF THE SAMPLE.

2. R. J. Archer<sup>16</sup> has calculated extensive tables giving thickness and index of refraction as a function of  $\Delta$  and  $\psi$  for non-absorbing films on silicon. These tables have been requested from Archer.
3. Mono-molecular layers of barium stearate, when properly deposited upon glass slides, are of known thickness and index of refraction.<sup>17</sup> These layers can be used to check the calculations of Vasicek and Archer.

At present, some difficulties exist in obtaining good accuracy of readings from the instrument. Small fluctuations in the input line voltage appear to cause variation in the intensity of the light source, thus causing fluctuations in the photometer readings. This has reduced the precision of the compensator and analyzer settings to about  $\pm 0.1$  degree, considerably greater than the capability ( $\pm 0.01$  degree) of the instrument. For accurate measurements of the thickness and index of refraction of very thin films, the precision must be close to  $\pm 0.01$  degree. (However, for some values of thickness and index of refraction, a precision of  $\pm 0.1$  degree is adequate.)

It is believed that a good voltage regulator will solve this problem. In addition, an analysis of certain small errors inherent in the ellipsometer (e. g. , correction factor for compensator not being exactly  $\lambda/4$ ) was found necessary.

#### (6) Masking Process

In Technical Note #2, the difficulties experienced in applying photolithographic masking techniques to the fabrication of tunnel cathodes were outlined. Further experiments in this direction disagreed with the assumption that the quality of the film to be masked was of great importance for the success of the method. Instead, it was found that using Kodak Photo Resist (instead of KMER) resulted in clean and reliable masking provided proper precautions were taken. The effectiveness of the masking was found to depend in a very sensitive fashion on the baking procedure and time of exposure to the ultraviolet light. However, if the latter was chosen for optimum coating adherence, it was found impossible to strip the coating cleanly in the later processing. Therefore, a slight underexposure is being used.

To simplify the fabrication procedure and, hopefully, to obtain smoother edges of the active area of the tunnel emitters, image reversal experiments were made in the photomasking process. In this way, the process of heavy oxidation of the structures as described in the previous Technical Notes is eliminated. A layer of photolacquer assumes the role of heavy oxide layer in defining the active area. The performance of annular tunnel emitters produced in this manner was exactly comparable with that of units made with the

previous masking process. No difficulties were encountered in obtaining a good vacuum with the photolacquer masking, nor with depositing conducting gold films of 90 Å thickness stretching from the active area on the photolacquer.

#### (7) Gold Film Preparation

In order to obtain reliable and reproducible results, the gold evaporation is performed fairly rapidly (for example, 10 Å/sec); otherwise, the resistance of the gold film does not show the square law dependence of its conductivity on its thickness, and, for a given amount of evaporated gold, produces a wide spread in conductivity. This is in agreement with the general theory of thin film formation which takes into account the mobility and nucleation of vapor atoms condensing on a substrate. Fast evaporation enhances a "two-dimensional growth" and, therefore, an early coherence of the forming thin film.

The thickness of the thin Au-films is determined from the weight of the evaporated Au-charge, from the relation between film thickness and weight of the charge for comparatively thick films (200-300 Å) by means of multiple beam interferometry.

#### (b) Emission Behavior of Tunnel Emitters

##### (1) Life Tests on Tunnel Cathodes

Some life tests were performed on annular structures of the following dimensions: inner diameter - 0.534 cm; outer diameter - 0.6 cm (see Figure 2b of the Technical Note #2). Useful dc operation of the devices has not as yet been accomplished. Therefore, in the life tests, the bias to the tunneling sandwich was applied in the form of rectangular pulses. For displaying the diode and emission characteristics triangular pulses were used as described in a previous report. The tunneling voltage of all the tested units was around seven volts. The tunneling insulator was prepared by anodic oxidation in tartaric acid solution. The top Au-film was kept at 90 Å thickness. The base aluminum film was prepared in the diffusion pump system described in part (a3) of this section.

With the first two batches, a negative resistive region tended to develop after repeated sweeping through the characteristic. This is illustrated in Figure 11. Later batches did not show this effect which might have been associated with the oil contamination previously referred to.

A typical example of normal behavior is given in Figure 12. A unit of one of these later batches was subjected to rectangular pulses of  $10^{-4}$  second length, the period between pulses being 1/120 second.

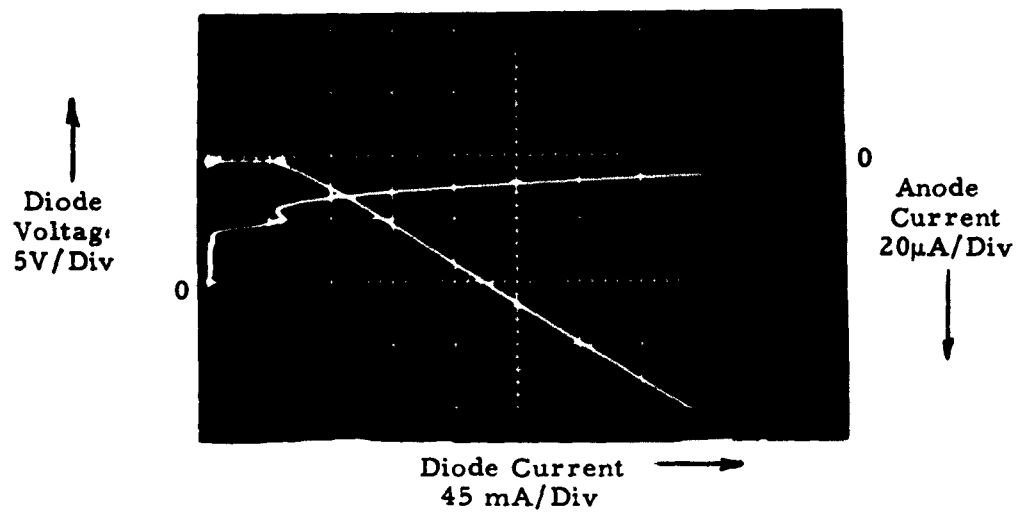


Figure 11. Abnormal V-I Characteristic of an Annular Tunnel Emitter Featuring a Negative Resistive Region.

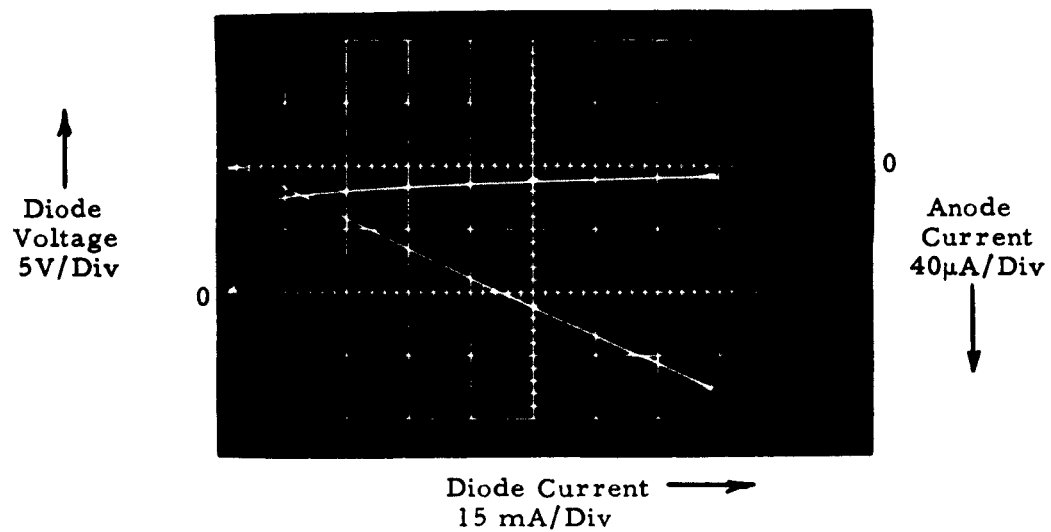


Figure 12: Typical Initial Diode and Emission Characteristics of Annular Tunnel Emitter. Display Time: 500  $\mu$ sec. Au-Film Thickness: 90 Å

After a quick drop in the initial emission, the cathode delivered 100  $\mu$ A at a circulating current of 200 mA. After a period of four hours the emission had deteriorated to 10  $\mu$ A with 400 mA readjusted diode current.

Further tests were performed on two units selected from a later batch which had the characteristics shown in Figure 12. Diode current and voltage stayed constant during these tests at 70 mA and 7.5 volts. Figure 13 and Figure 14 show the deterioration of the emitted current during time of operation. For the first unit, a pulse length of 0.1 millisecond was chosen; for the second unit, a pulse length of 1 millisecond. With a separation between pulses of 1/120 second, this corresponds to a duty cycle of the order of 1% in the first case, and 10% in the second case.

The complexity of the deterioration phenomenon is demonstrated by the following experiment which was conducted with the second unit after the above test: The diode current was increased from 70 mA to 200 mA with a consequent increase of the emitted current from 27  $\mu$ A to 128  $\mu$ A. The unit operated with these values for about 10 minutes without noticeable change, and then suddenly developed a short. Operation was restored to the previous values by applying strong current pulses of about two amps and a length of 0.1 millisecond. The unit then operated very steadily without change in the emission for another 1 1/2 hours before it again developed a short circuit.

This last experiment suggests that localized weak spots in the insulator were responsible for the cathode failure. These spots were isolated by applying the strong current pulses which burned off their contact with the Au-film. From these results, it appears that high current operation of the units may be beneficial to their stability. This is in agreement with the general observation that in slowly sweeping through the I-V diode characteristic the most destructive instabilities seem to occur at low current levels.

The following model would explain such a behavior: At low voltages and currents, the weak areas in the insulator are mostly responsible for the current transfer through the insulator, and they heat up accordingly to the point of destruction. At higher voltages, the tunneling through the sound areas of the insulator is taking over the major portion of the current, thus bypassing the resistance represented by the weak spots.

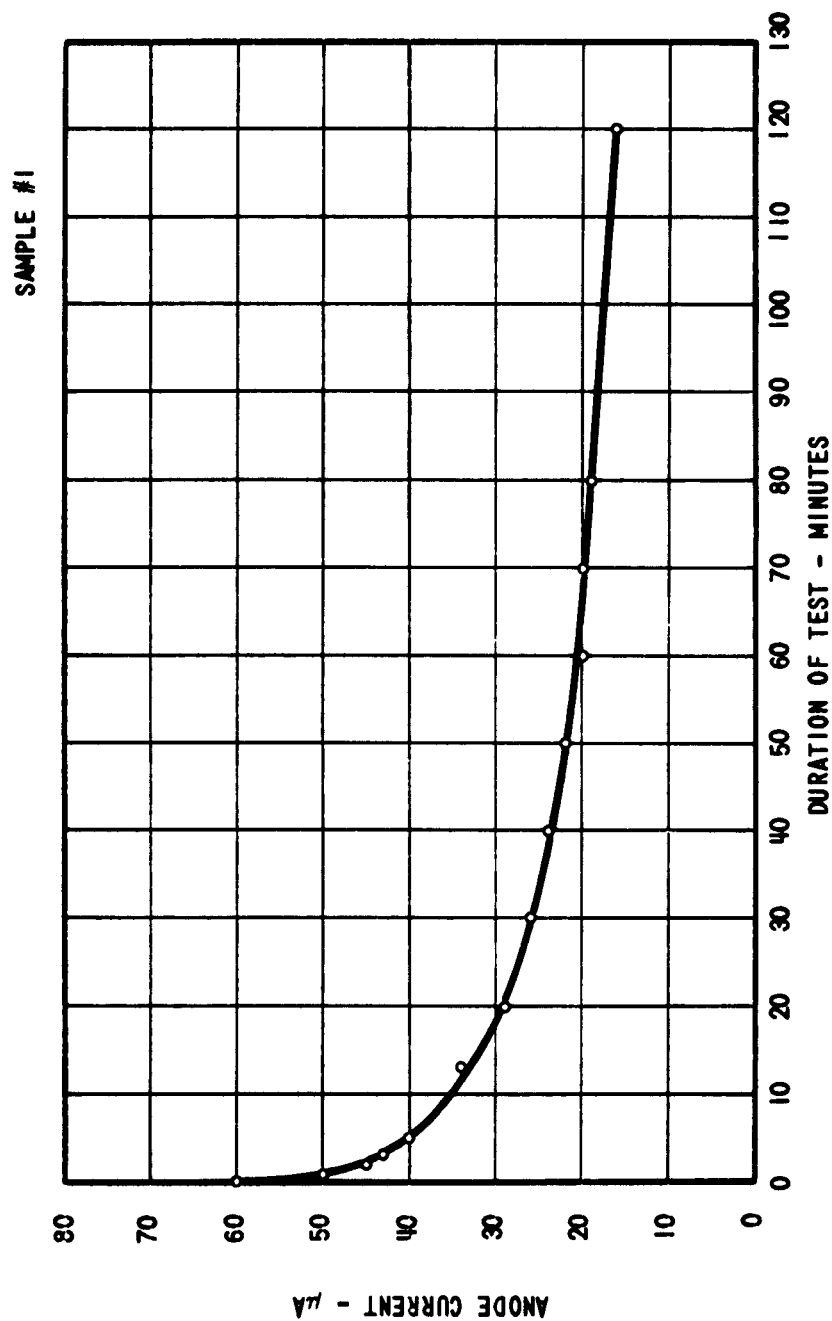


FIGURE 13  
 DETERIORATION OF EMISSION FROM AN ANNULAR TUNNEL CATHODE UNDER  
 PULSED OPERATION. WIDTH OF THE RECTANGULAR PULSES: 0.1 MILLISEC,  
 DUTY CYCLE 1.2%. DIODE VOLTAGE: 7.5 VOLTS, DIODE CURRENT: 70 mA



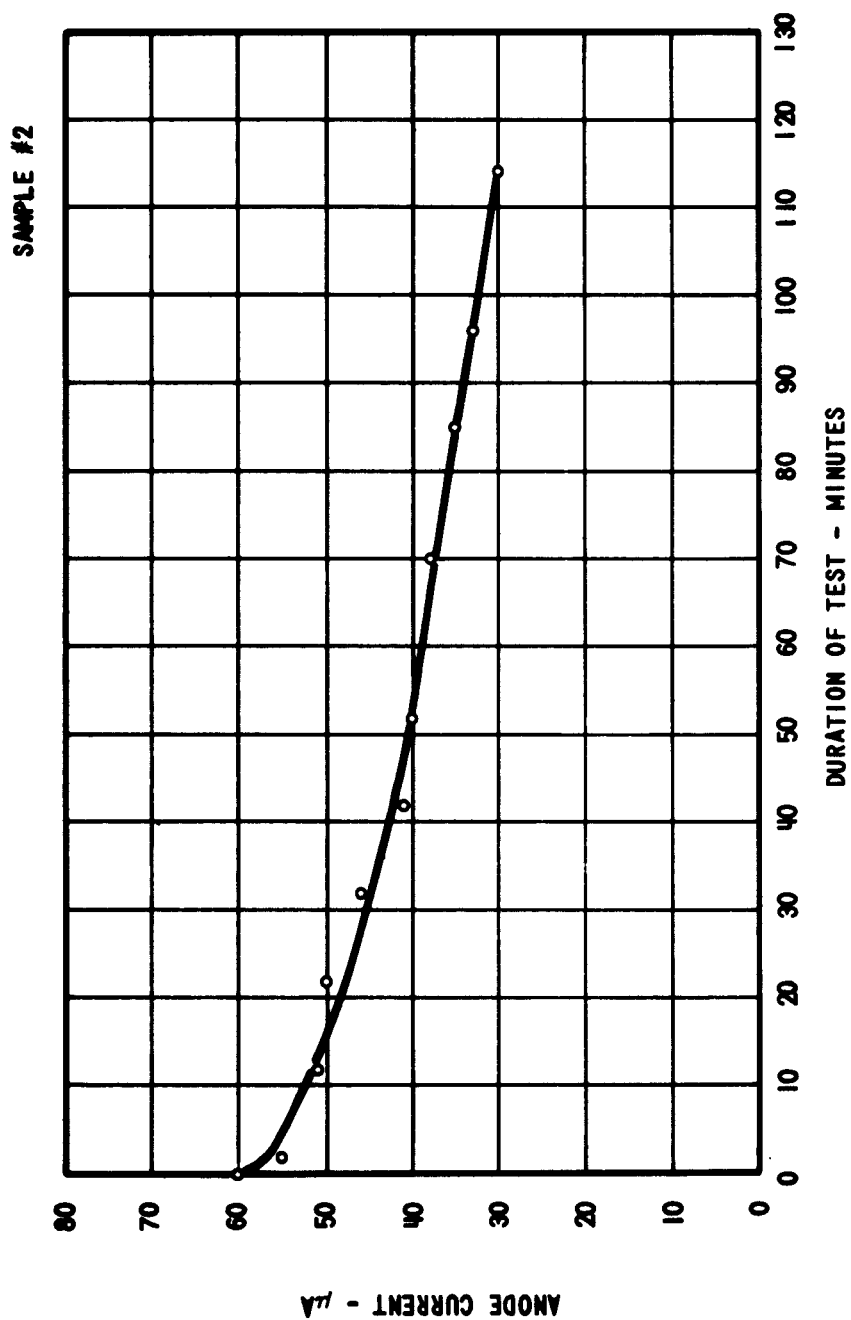


FIGURE 14  
DETERIORATION OF EMISSION FROM AN ANNULAR TUNNEL CATHODE UNDER  
PULSED OPERATION. WIDTH OF THE RECTANGULAR PULSES: 1 MILLISEC,  
DUTY CYCLE: 11%. DIODE VOLTAGE: 7.3 VOLTS DIODE CURRENT: 70 mA

(2) Evaluation of a Theoretical Model Describing the Experimentally Observed Behavior of Al-Al<sub>2</sub>O<sub>3</sub>-Au Emitters.

Measurements of the diode and emission characteristics have been taken for various Au-film thicknesses (in general 90 Å, 135 Å, 180 Å) and insulator thicknesses (ranging from about 40 to 300 Å), and the influence of depositing barium onto the emitting surface has been studied for various insulator and gold film thicknesses. Since thermal breakdown proved to be a problem with the investigated structures, the measurements were taken with sufficiently short current pulse to ascertain that the intrinsic behavior of the structures was observed. Emission current densities of several amperes per sq. cm. were obtained with some of the devices.

The experiments confirmed some basic findings by C. A. Mead which he had obtained on Be-BeO-Au structures.<sup>12</sup> These are:

A) If the tunneling voltage (i. e. the voltage at which significant tunneling occurs) is greater by 0.5-1 eV, than the vacuum work function of the Au-film, the ratio of emitted current to circulating diode current is nearly constant over a range of currents which may differ by at least two orders of magnitude.

B) The emitted current  $I_e$  decreases with the Au-film thickness according to the law:

$$I_e(x) = I_e(o) e^{-x/\lambda_m}$$

where  $x$  = thickness of the top metal film,  $\lambda_m$  = attenuation length for the emission current. The current attenuation length was found dependent on the tunneling voltage and varied between 35 and 20 Å for tunneling voltages between 6 and 20 volts (corresponding to approximate insulator thicknesses between 80 and 260 Å).

In addition, it was found that: C) The insulator thickness does not have a pronounced effect on the transfer ratio at constant field (emitted current/circulating diode current) provided that the tunneling voltage was larger by 0.5 - 1 eV than the vacuum work function of the top metal film.

D) The deposition of an optimum layer of barium onto the emitting surface always caused an increase of the emission by nearly one order of magnitude, independent of Au-film thickness, and insulator thickness. Changes in the diode I-V characteristic under the influence of the deposited barium were not apparent. The latter observations are in contrast to the findings of other workers.<sup>13</sup> It is supposed that in their experiments a number of fairly large pinholes in the top film

permitted the work function reducing component to get in direct contact with the insulator film. Our findings on the effect of the barium are consistent with the behavior of the tunnel cathode at zero extrapolated Au-film thickness. It is indicated that, in this case, about 10% of the tunneled electrons can escape over the work function barrier. The work function reduction by the barium enhances this ratio by a factor of nearly ten so as to permit almost all electrons to escape.

E) The mechanism of current injection into the insulator appears to be tunneling rather than thermionic emission over a field-reduced barrier (Schottky-emission). This is indicated by the very sharp bend occurring in the I-V characteristic. There is a critical voltage above which the diode current rise is very steep. Another proof is the fact that in order to obtain emission the diode voltage must be equal to or larger than the vacuum voltage function of the top metal film.

A model for the functioning of the Al-Al<sub>2</sub>O<sub>3</sub>-Au tunnel cathode that seems to fit in with the above observations is illustrated in Figure 15. Electrons tunnel from the base metal into the conduction band of the insulator constituting the current  $I_c$ . In there they suffer heavy energy losses by inelastic collisions involving phonons and other electrons so that they arrive at the interface between insulator and top metal at energy levels close to the conduction band edge. This process is more or less independent of the thickness of the insulator. The strong proportionality of the emitted current to the diode current suggests that the current  $I_v$  resulting from tunneling from the valence band into the metal is small compared to  $I_c$ .<sup>11</sup> The conduction band edge at the interface is situated lower in energy than the work function of the gold into the vacuum. Therefore, only about 10% of the electrons arriving in the top film have sufficient energy to overcome the vacuum barrier, even for an Au-film thickness approaching zero.

### (3) Setup for Investigating the Uniformity of the Emission Over the Active Surface.

In the present tunnel emitters, the transfer ratio is rather small and most of the diode current is conducted away through the thin top metal film. The resistance of this film is responsible for a voltage drop developing across the active area. Since the current through the insulator is a sensitive function of the applied voltage, the major part of the emission may very well be confined to the edges of the active area. In addition, since the tunneling current is a very sensitive function of the insulator thickness for a given applied voltage, a display of the emission distribution will produce evidence about the uniformity of the insulator. The operation of the tunnel cathode requires the utmost in dielectric strength from the tunneling insulator; therefore, an even loading of the insulator area is most important.

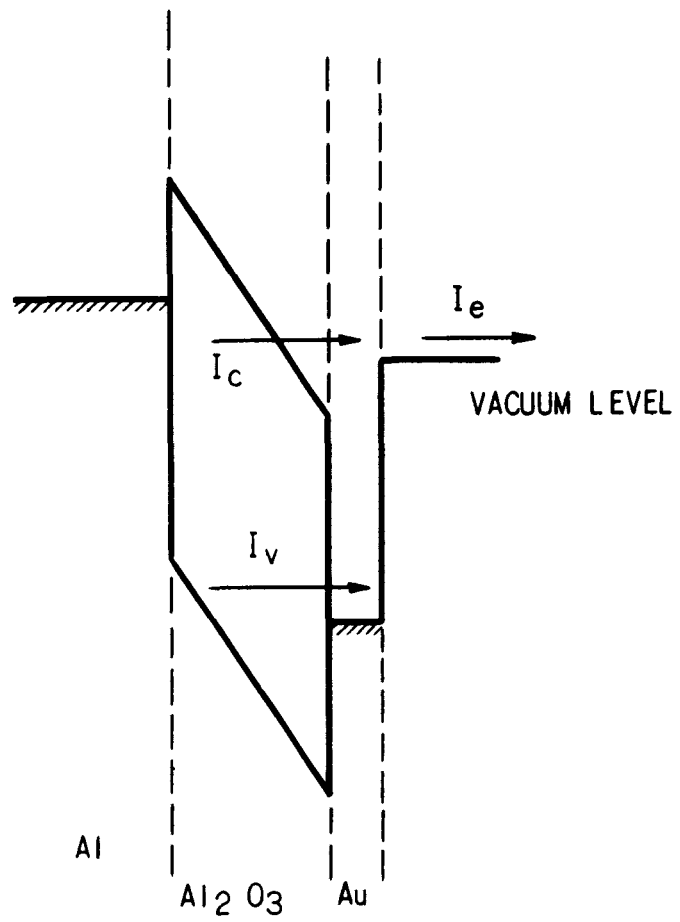


FIGURE 15 BASIC ENERGY DIAGRAM OF A TUNNEL CATHODE

For the visual display of the spatial emission distribution, a demountable projection tube is being built which will permit a display with dc or pulsed operation of the cathode. The tube will adapt to different types of cathodes, e. g. circular or annular shapes of various dimensions. For adjusting the image on the projection screen, a focusing electrode is provided which is adjustable from the outside by a bellows arrangement.

#### (4) Setup For Measuring the Velocity Distribution of the Emitted Electrons.

To obtain additional information about the emission mechanism and to reveal the noise properties of the cathode, an evaluation of the velocity distribution of the emitted electrons is desirable. For this reason, a setup is being built which permits the measurement of the velocity distribution by the retarding potential method with either pulsed or dc operation of the cathode. The present test tube involves the cathode, a molybdenum aperture, and a single crystal tungsten anode.<sup>18</sup> The spacing between these parts is 1/10 inch. A longitudinal magnetic field will be used for focusing. Currently, the setup is being tested for its reliability by using a thermionic cathode.

#### (c) Consideration of Tunnel Cathode Dimensions Suitable for a 10 kMc Traveling-Wave Tube

In this section, the electrical parameters of a traveling-wave tube at X-band using a tunnel cathode will be investigated. The desired gain of this tube is  $G = 20$  db at 10 Gc. Three cases will be considered, a hollow beam TWT and two solid beam TWTs having different beam current densities.

##### 1. Hollow Beam Case

Choosing the synchronous voltage  $V_s = 1220$  V the propagation constant is

$$\gamma = \frac{3170}{\lambda \sqrt{V_s}} = 30.2$$

$\gamma a = 3.5$  is the optimum for a hollow beam of  $b/a = 0.7$ , where  $a$  is the mean helix radius and  $b$  is the radius of the beam. Hence, the mean helix radius is

$$a = 0.116 \text{ cm} = 0.0456''$$

The coupling impedance at the axis is<sup>19</sup>

$$K_o = 7250 \frac{1}{\lambda^2} \frac{1}{\beta_o^2} \left( \frac{c}{V_p} \right)^3 e^{-2\pi \frac{c}{V_p} \frac{a}{\lambda}} = 72.5 \text{ ohms.}$$

$c$  = velocity of light and  $V_p$  = phase velocity.

Because of the fact that this impedance is valid only for the sheath helix, and because of dielectric loading, the actual impedance will be approximately one-half the computed value. To arrive at the effective coupling impedance for the hollow beam of outer radius  $b$  the impedance at the axis has to be multiplied by Pierce's<sup>20</sup> empirical relation

$$F(\gamma a) = 7.154 e^{-0.6664 \gamma a},$$

which amounts to  $F(\gamma a) = 2.2$  for  $\gamma a = 3.5$  and  $b/a = .7$ . Therefore, the effective coupling impedance is

$$K = 80 \text{ ohms.}$$

Let the beam current be  $10^{-4}$  A. Assuming a ratio of the inner and outer beam radii of 0.6, the area of the beam annulus becomes  $F = 1.36 \times 10^{-2} \text{ cm}^2$ , and the beam current density is  $i_0 = 0.735 \times 10^{-2} \text{ A/cm}^2$ .

Pierce's gain parameter is calculated to be

$$C^3 = \frac{I_0 K}{4 V_0} = 1.54 \times 10^{-6}$$

and

$$C = 1.155 \times 10^{-2}.$$

Here it has been assumed  $V_0/V_s \approx 1$  since the gain parameter  $C$  and the space-charge parameter  $QC$  are small quantities so that  $(1 + bC)^2 \approx 1$  where  $b$  is the velocity parameter  $b = \sqrt{4 QC}$ . The plasma frequency is

$$\omega_p = 1.83 \times 10^{10} \frac{i_0^{1/2}}{V_0^{1/4}} = 0.0266 \times 10^{10} \frac{1}{s}$$

The plasma reduction factor for the hollow beam is obtained from Branch and Mihran.<sup>21</sup> For  $H = h/b = 0.6$ , where  $h$  is the inner radius of the hollow beam,  $R = a/b = 1.43$  and  $\gamma(b - h) = 0.98$  the reduction factor is  $s = 0.58$ . Now, the space charge parameter can be calculated

$$4 QC \approx \left( \frac{s \frac{\omega_e}{\omega}}{c} \right)^2 = 0.0359$$

$QC = 0.009$ , and the gain factor  $B = 47$  (from Pierce).

The gain of a traveling-wave amplifier can be written

$$G = A + BCN - \alpha L.$$

The sum of the total initial loss parameter A and the cold loss L multiplied by the gain reduction factor  $\alpha$  at X-band is of the order  $A - \alpha L = 20$  db. Therefore, the gain has to be  $BCN = 40$  db to result in the net gain of 20 db.

The only parameter which has not been fixed yet is the number of wavelengths on the structure N.

It is  $N = l/\lambda = 500/V_O = 40/BC = 73.6$ . Consequently, the length of the active helix has to be

$$l = 15.1 \text{ cm} = 5.95''$$

to produce the desired gain of 20 db.

## 2. Solid Beam Case

Assuming  $\gamma_a = 2.0$  and using the same beam current and voltage as in case (a), the parameters are computed in a similar manner:

$$\gamma_a = 2.0$$

$$a = 0.0662 \text{ cm} = 0.026''.$$

The coupling impedance for a solid beam ( $b/a = 0.5$ ) is taken from Pierce's book

$$K = 31.7 \text{ ohms.}$$

Gain parameter

$$C^3 = 0.65 \times 10^{-6}$$

$$C = 0.865 \times 10^{-2}$$

Beam radius  $b = 0.0331 \text{ cm}$

Beam cross-section  $F = 34.5 \times 10^{-4} \text{ cm}^2$

Beam current density  $i_0 = 0.029 \text{ A/cm}^2$

Plasma frequency  $\omega_p = 0.0527 \times 10^{10} \text{ 1/s}$

Plasma reduction factor  $s = 0.545$

Space charge parameter  $QC = 0.07$

Gain factor  $B = 43$

Number of wavelengths  $N = 107.5$

Active length  $l = 22.4 \text{ cm} = 8.83''.$

Since the current density is too high for the presently available tunnel cathode, the parameters are calculated for a reduced current density which can be obtained in the available tunnel cathodes.

Beam current density  $i_0 = 0.01 \text{ A/cm}^2$   
Beam current  $I_0 = 10^{-4} \text{ A}$   
Beam radius  $b = 0.0565 \text{ cm} = 0.0222''$   
Mean helix radius  $a = 0.113 \text{ cm} = 0.0445''$

$$\gamma a = 3.41$$

Coupling impedance  $K = 2.74 \text{ ohms}$   
Gain parameter  $C^3 = 0.0561 \times 10^{-6}$   
 $C = 0.383 \times 10^{-2}$   
Plasma frequency  $\omega_p = 0.031 \times 10^{10} \text{ 1/s}$   
Plasma reduction factor  $s = 0.72$   
Space charge parameter  $QC = 0.215$   
Gain factor  $B = 38$   
Number of wavelengths  $N = 275$   
Active helix length  $l = 57.2 \text{ cm} = 22.5''$

### III. Conclusions and Work Planned for Next Quarter

The cathode performance so far attained is not adequate for use in a 10 kMc amplifier; hence, the design and construction of a traveling-wave structure has not as yet been initiated.

Basically, the Al-Al<sub>2</sub>O<sub>3</sub>-Au structure gives the right kind of operation. A serious limitation of performance is imposed by the strong attenuation of the energetic electrons in the top metal film. A gold film of only fifty Angstroms thickness is expected to limit the transfer ratio to about ten percent. The most serious difficulty experienced to date has been the short dc lifetime of the tunnel emitters so far tested. It is believed, however, that with improved uniformity of the tunneling insulator a satisfactory operation of the tunnel cathode over extended periods should be possible.

It may be concluded from our calculations that only the hollow beam cathode results in practical dimensions for achieving the goals of this project. In the case of the solid beam, the active helix length required is too long. Unless the beam current density can be increased, a hollow beam has to be used despite the small dimensions of the beam.



During the next quarter, it is planned to continue efforts to improve the insulator uniformity and breakdown strength so as to yield useful dc life. In line with this, ellipsometric measurements of thin insulator films should be accomplished. The uniformity of emission of selected cathodes will be determined using the projection tube now being set up. Preliminary measurements of the velocity distribution of electrons emitted from tunnel cathodes will be obtained. Thin film cathodes of the correct dimensions for use in a 10-gigacycle traveling-wave amplifier will be constructed.

Comparison with the data obtained by C. A. Mead on BE-BeO-Au structures<sup>12</sup> shows that, in this case, the attenuation in the top Au-film was about three times larger than that observed for Al-Al<sub>2</sub>O<sub>3</sub>-Au structures. However, the transfer ratio for an Au-film thickness approaching zero is one order of magnitude smaller in the first case as compared to the second one. This suggests that the conduction band edge of the BeO is situated lower with respect to the vacuum level than that of the Al<sub>2</sub>O<sub>3</sub>. The discrepancy in attenuation length may be interpreted, perhaps, as resulting from the different structure of the gold-film deposited onto the two different insulators, or by the assumption that the average energy of the electrons from the BeO passing through the Au-film is smaller than the average energy of electrons from the Al<sub>2</sub>O<sub>3</sub>. This would result from the general assumption that the mean free path of hot electrons passing through a metal is a strongly decreasing function with excess energy above the Fermi level.<sup>14</sup> To obtain some evidence about the energy dependence of the attenuation path, the transfer ratio of a barium-treated sample was observed at a low tunneling voltage (3-4 Volts) at two different gold-film thicknesses. However, the attenuation path resulting from this experiment was not larger than the previously observed values for tunneling voltages which were several volts higher.

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